Present Status and Future Prospects for Ionospheric Propagation Corrections for Precise Time Transfer Using GPS

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Abstract

The ionosphere can be the greatest variable source of error in precise time transfer using GPS satellites. For single frequency GPS users the iono spheric correction algorithm can provide an approximate 50% r.m.s. correction to the time delay, but users who desire a more complete correction must make actual measurements of ionospheric time delay along the path to the GPS satel lite. Fortunately, at least three commercial GPS receivers, specifically designed to measure and correct for ionospheric time delay, are now, or soon will be, available. Initial operation with two different types of GPS iono spheric receivers has demonstrated a high degree of accuracy in measuring the ionospheric group delay. Results of these measurements will be presented.

For those who use a model to correct for ionospheric time delay, it is tempting to use daily values of solar 10.7 cm radio flux to correct a monthly average ionospheric time delay model for each day's operation. The results of correlation of daily maximum ionospheric time delay against solar radio flux values show a poor correction will be obtained by this procedure. Prospects for improving ionospheric corrections during the declining phase of the present solar cycle will be discussed.

INTRODUCTION

It is well known that attempts to obtain precise time by means of monitoring the clocks on the GPS satellites can be limited by the time delay of the earth's ionosphere. This additional time delay is due to the group delay of the modulation of the 1.023 MHz and 10.23 MHz modulation which carry the modulation, or time information on the signal. The amount of this additional time delay can be expressed as:

$$\Delta t = 40.3/(cf^2)\mathrm{TEC} \qquad \text{(seconds)}$$

where c is the velocity of light, in m/s and f is the carrier frequency, in Hertz.

TEC is the number of free electrons in a unit column, having a cross section of one square meter, the earth's ionosphere along the path between the satellite and the ground monitoring station. One TEC unit is called 1×10^{16} el/m^2.

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Typical monthly median values of this additional time delay are shown in Figure 1a for 2000 U. T. for the solar maximum year of 1990. Note that the highest values of ionospheric vertical time delay are 50 nanoseconds. To convert vertical time delay values to those at a slant elevation angle a mean ionospheric height of 400 km is generally used. Thus, at low elevation angles, even as low as 5 degrees, the time delay will be only approximately three times as high as the vertical values.

During a period of minimum solar activity the ionospheric time delay values will be much lower. Figure 1b illustrates the results of a monthly median model of time delay for 1995, a year of expected minimum in solar activity. Note that the maximum value of ionospheric time delay is only 20 nanoseconds, and for much of the time over the entire globe, the maximum median vertical ionospheric time delay is less than 5 nanoseconds. These model representations are of monthly median conditions only.

IONOSPHERIC DAY-TO-DAY VARIABILITY

The variability of ionospheric time delay about the monthly median values for any month is approximately normally distributed about the mean value with a standard deviation from 20 to 25%, especially during the daytime hours when the absolute values are the highest. Figure 2 illustrates the day-to-day variability of ionospheric time delay over an entire year, for a mid-latitude station located near Boston, MA. The units in Figure 3 are in 10^{16} el/m^2 column. To obtain nanoseconds of time delay at L1, the 1.575 GHz GPS freq uency, you must divide the TEC ordinate scale by 1.85. Note that each of the monthly overplots has a relatively large spread about its monthly median values. A similar variability is found for ionospheric time delay measured from other mid-latitude stations.

CORRECTING FOR IONOSPHERIC TIME DELAY

I. THE GPS IONOSPHERIC TIME DELAY ALGORITHM

The GPS satellites transmit, as part of their data message, coefficients designed to correct for approximately 50% of the root mean square, (rms) ionospheric time delay error. Tests of the performance of this algorithm against a large amount of mid-latitude ionospheric electron content data have shown that, indeed, at least a 50% rms correction is achieved. Klobuchar and Doherty, (1990), have looked at the statistics of the behavior of ionospheric time delay for a number of stations, and also have shown the statistics of the residual errors after applying the GPS ionospheric time delay algorithm.

Figure 3a illustrates the statistics of the variability of the earth's mean daytime ionosphere for a low mid-latitude station, Ramey, Puerto Rico. The three seasons of a solar maximum year, 1981, are represented separately in Figure 3a. The solid points represent the actual behavior of ionospheric range error, in meters at L1, versus cumulative probability. One meter represents 3 nanoseconds of time delay. The abscissa is scaled in a manner such that a normal distribution is represented by a straight line in this figure. Note that for all three seasons the ionospheric time delay behavior is approximately normally distributed.

Also shown in Figure 3a is the remaining ionospheric range error after the use of the GPS single frequency user algorithm to correct for ionospheric range error. Note that, for all but the approximate lowest 0.01 fraction of the curves, the use of the algorithm considerably lowered the ionospheric

range error.

Figures 4a and 4b illustrate similar data for a station located in Hamilton, MA also for the solar maximum year of 1981. Again the GPS single frequency user ionospheric algorithm provides a large improvement over the actual data for the daytime values for all three seasons. The large departure from near normal distribution of the data above 0.99 on the cumulative proba bility curve for the equinox daytime values shown in figure 4a is due to a single magnetic storm which occurred during that season.

Other similar comparisons of actual ionospheric measurements against the GPS ionospheric algorithm have been made for stations located in Hawaii and Tromso, Norway. The results of comparisons at all these stations show that the algorithm works best during times when the actual ionospheric range errors are the greatest, which is when it is highly desirable that it should work the best. During the nighttime hours, when the absolute values of ionospheric time delay are low, the algorithm does not correct as well, but during those hours of low absolute values, a poorer correction can more easily be tolerated.

II. MEASUREMENTS OF IONOSPHERIC TIME DELAY

If the residual errors in obtaining precise time from GPS signals, after using the single frequency ionospheric correction algorithm, are still too large for precise time transfer using GPS, then an actual measurement of the ionospheric time delay must be made, preferably along the line of sight from the same GPS satellite from which the time transfer is being attempted. Davis, et. al. (1991) have described a receiving system specifically designed to measure ionospheric time delay from multiple GPS satellites. Figure 5 illustrates an example of TEC data obtained from this type of code-free rec eiving system. Also shown in this figure is the TEC obtained by the Faraday rotation technique. The agreement is excellent, indicating that the NIST ionospheric monitoring system works as desired.

The code-free GPS ionospheric receiving system is relatively inexpensive and has been proven to yield satisfactory values of ionospheric time delay to an approximate accuracy of a few nanoseconds, certainly better that ten nano seconds, but, at present, not as good as one nanosecond. One potential problem for ionospheric corrections is the unknown offset of the 10.23 MHz modulation on the L1 and L2 frequencies on each GPS satellite. Each satellite has a different modulation offset, called tgd, which is transmitted as part of each satellite message. Unfortunately, when compared against other measure ments of ionospheric electron content the transmitted tgd values do not yield as precise absolute ionospheric electron content as desired. Several groups are presently studying ways of improving the accuracy of this bias.

CORRELATION OF IONOSPHERIC TIME DELAY WITH SOLAR RADIO FLUX

Ionization in the earth's ionosphere is produced by ultra-violet, UV, emissions from the sun. Thus, it is tempting to use a standard measure of short term solar activity, the solar radio flux on 10.7 cm wavelength, to correlate with the day-to-day variability of the ionosphere. Unfortunately, this does not work well due to many other complicating factors in the produc tion, loss and transport of ionization in the earth's ionosphere which are still subjects of active research in the ionospheric community.

As an example of attempts to correlate ionospheric time delay against F10.7, Figure 6a illustrates correlations of mean daytime values of TEC against 10.7 cm solar radio flux for each of the 12 months of 1981, a year of very high solar activity. The coefficient of correlation, along with the 95% confidence intervals is given for each month. Note that, for most months, the correlation is low. The highest values of correlation occur during April and December and even during those months the correlation coefficient is only 0.66.

If the magnetically disturbed days are removed from each month, the resulting correlation does not improve significantly, as indicated in Figure 6b. Note that the month of April now has a negligible correlation, while that for May and some of the winter months has improved a bit. Over half the months of the year exhibit a negligible correlation of mean daytime ionospheric time delay against the standard F10.7 radio measure of solar UV flux.

LONG TERM SOLAR FLUX

We are now in the declining phase of the current 11 year solar cycle, as shown in Figure 7. At present the predictions of long term solar activity are not reliable. Thus, an average solar cycle maximum is perhaps the best that can be predicted at this time. As we approach the end of the current solar cycle, expected to be in the mid-1990s, predictions of the next cycle should be more reliable since the method which has had moderate success in long term predictions has relied on recurrent magnetic storms during the last few years of a solar cycle. During the solar minimum conditions expected in the mid- 1990s the absolute values of ionospheric time delay should be from one half to one fourth their values during solar maximum.

DISCUSSION AND CONCLUSIONS

Ionospheric time delay limits the accuracy of precise time transfer, by using the single frequency signal from the GPS satellites, to a few tens of nanoseconds. The ionospheric time delay algorithm can improve the ionospheric rms error by at least 50%, but the remaining errors may still be too large for time transfer at the ten nanosecond level.

The best method of correcting for the effects of ionospheric time delay is simply to measure it directly by means of a relatively inexpensive code-free receiving system designed specifically for that purpose. The overall accuracy of such a system is certainly better than ten nanoseconds, but probably not yet at the one nanosecond level. Time transfer at the sub-nanosecond level using GPS will be very difficult to accomplish due to the effects of the time delay of the earth's ionosphere.

The long term solar activity of the present solar cycle is now in its declining phase, and can be expected to reach a minimum in activity in the mid-1990s. The best current estimates of the next solar maximum are for it to occur approximately in the year 2000, and to be of average strength. By the mid-1990s the predictions of the strength of the next solar maximum should be greatly improved.

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Albuquerque, NM, September 1991.

2. Klobuchar, J. A. and P. H. Doherty, *"The Statistics of Ionospheric Time Delay for GPS Ranging on L1"*, Proceedings of ION GPS-90, The Institute of Navigation, September 1990.

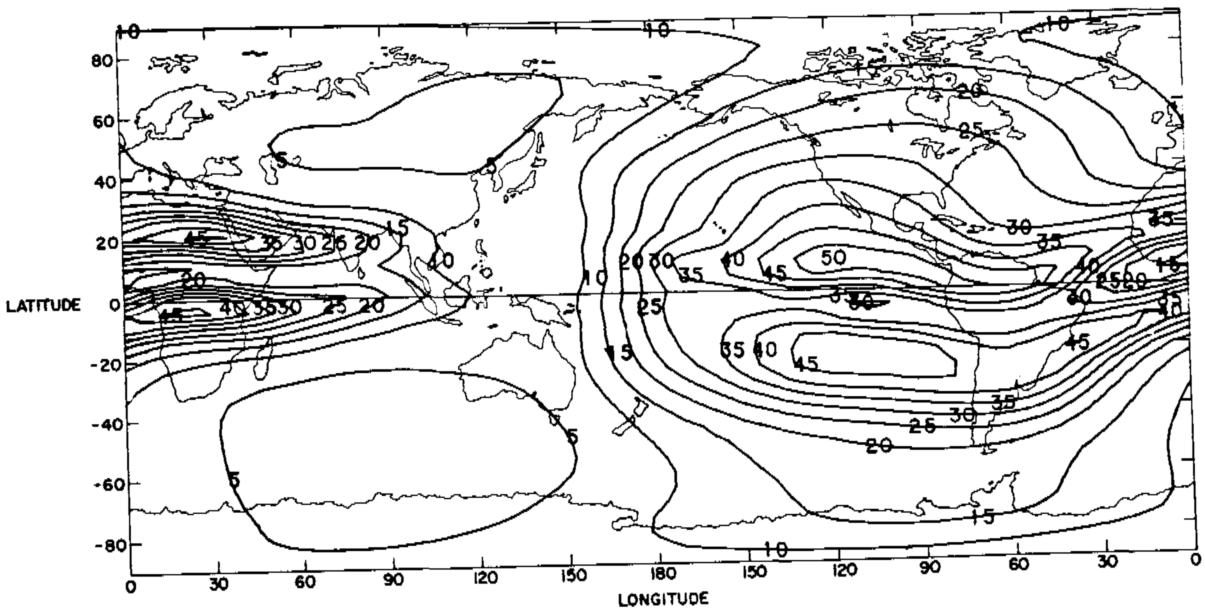

Figure 1a. Contours of world-wide monthly time delay for March 1990, a solar maximum year.

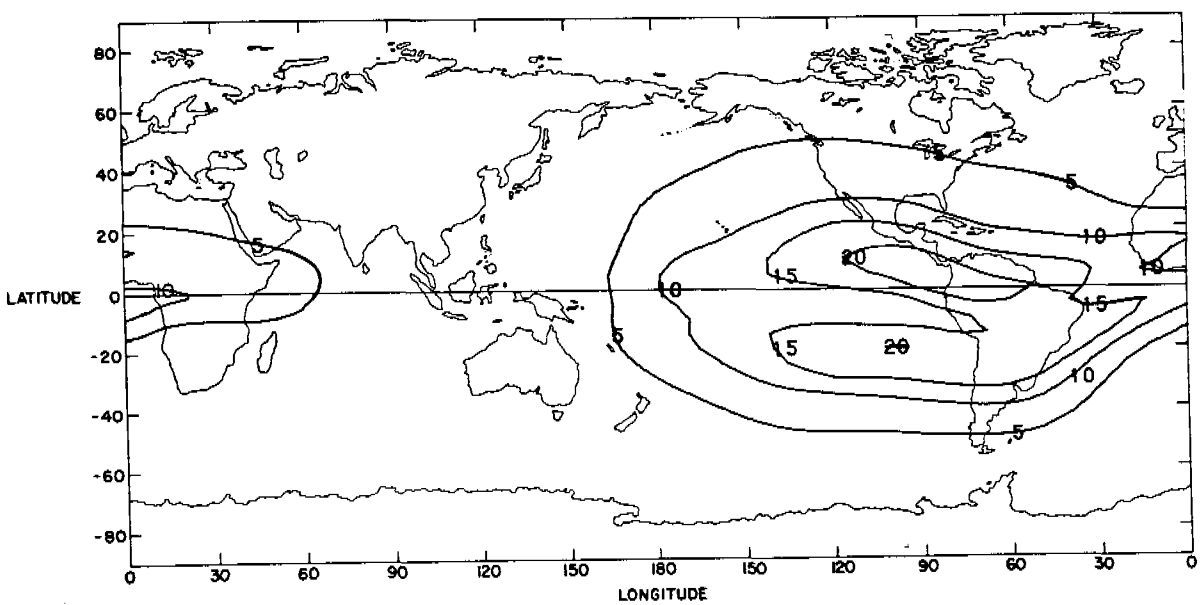

Figure 1b. Contours of world-wide monthly time delay for March 1995, a year of expected solar minimum activity.

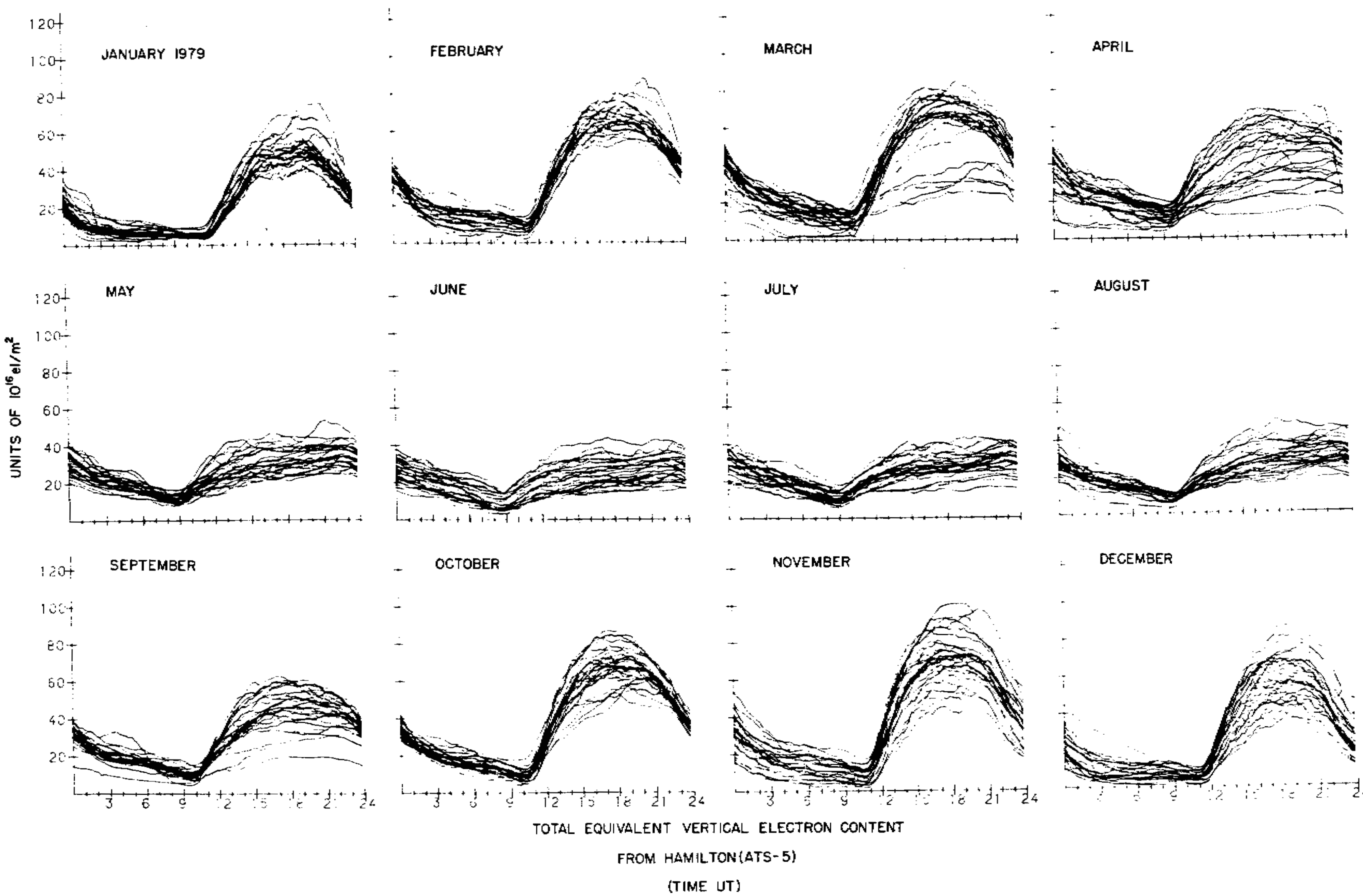

Figure 2. Monthly overplots of ionospheric TEC for 1979, a year of high solar activity.

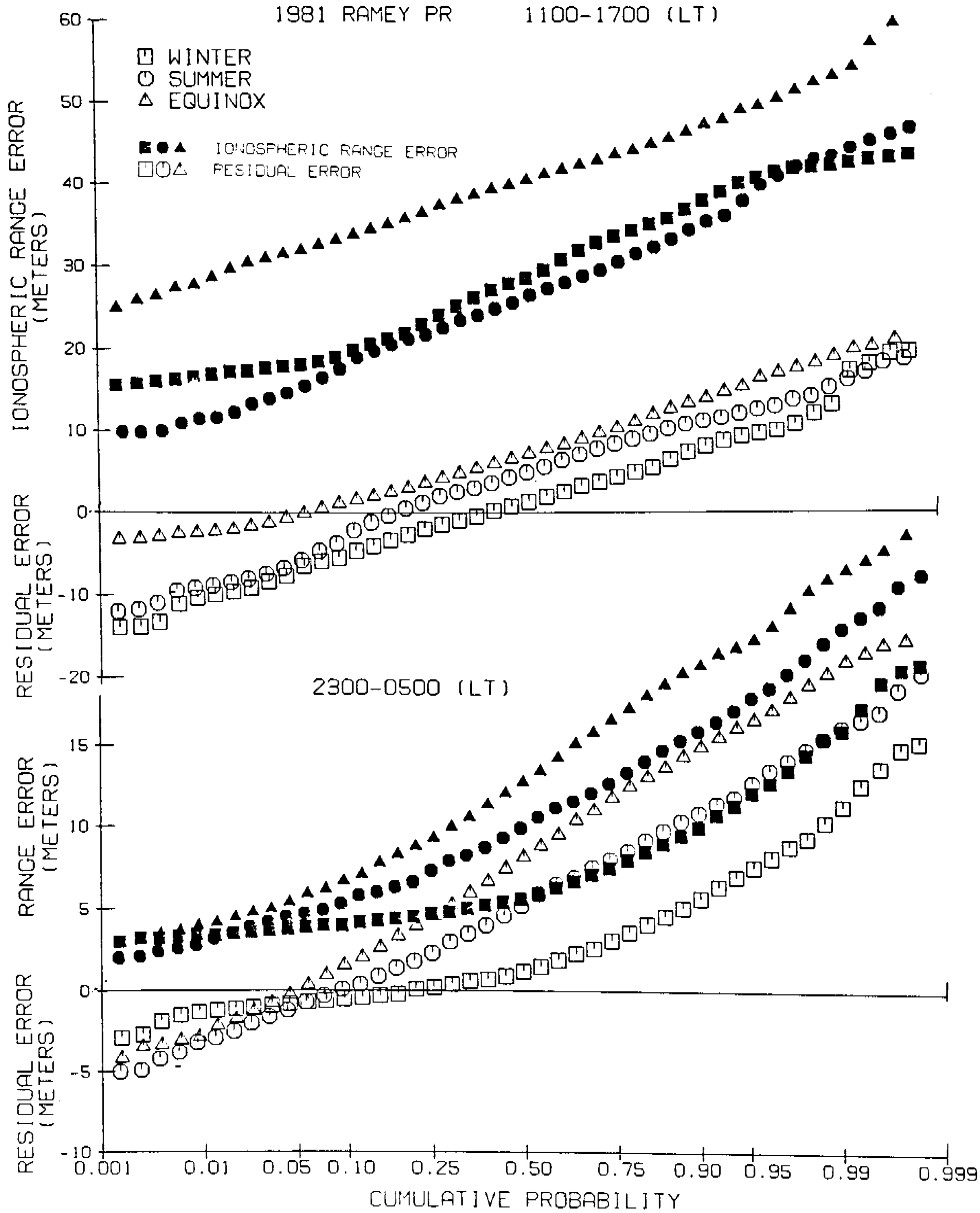

Figure 3. Cumulative probability of ionospheric range error for Ramey, PR for three seasons during 1981, a year of high solar activity. Also shown is the residual error after applying the GPS single frequency user ionospheric error algorithm.
3a, (top) is for mean daytime. 3b, (bottom) is for mean nighttime.

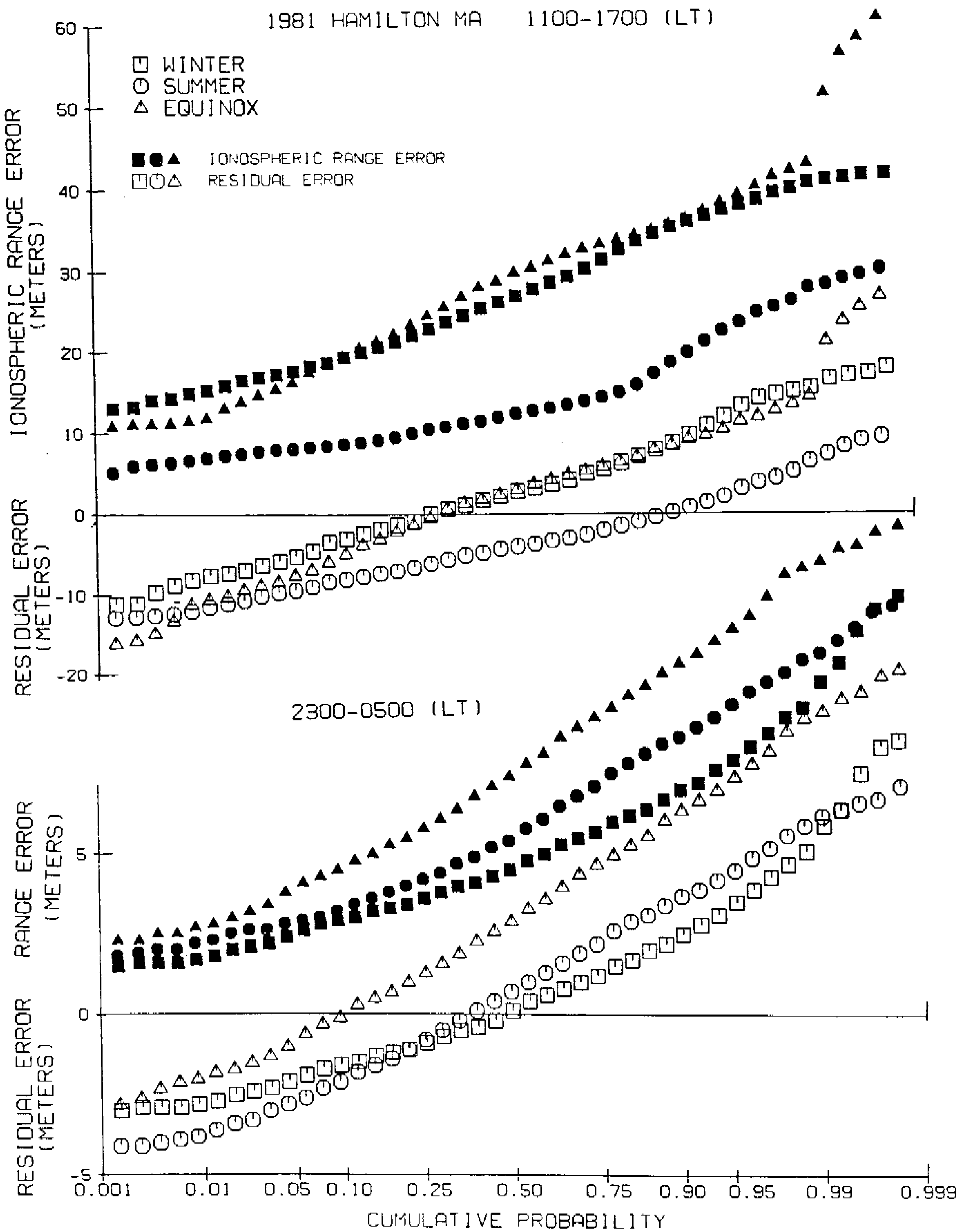

Figure 4. Cumulative probability of ionospheric range error for Hamilton, MA for three seasons during 1981, a year of high solar activity. Also shown is the residual error after applying the GPS single frequency user ionospheric error algorithm.
4a, (top) is for mean daytime. 4b, (bottom) is for mean nighttime.

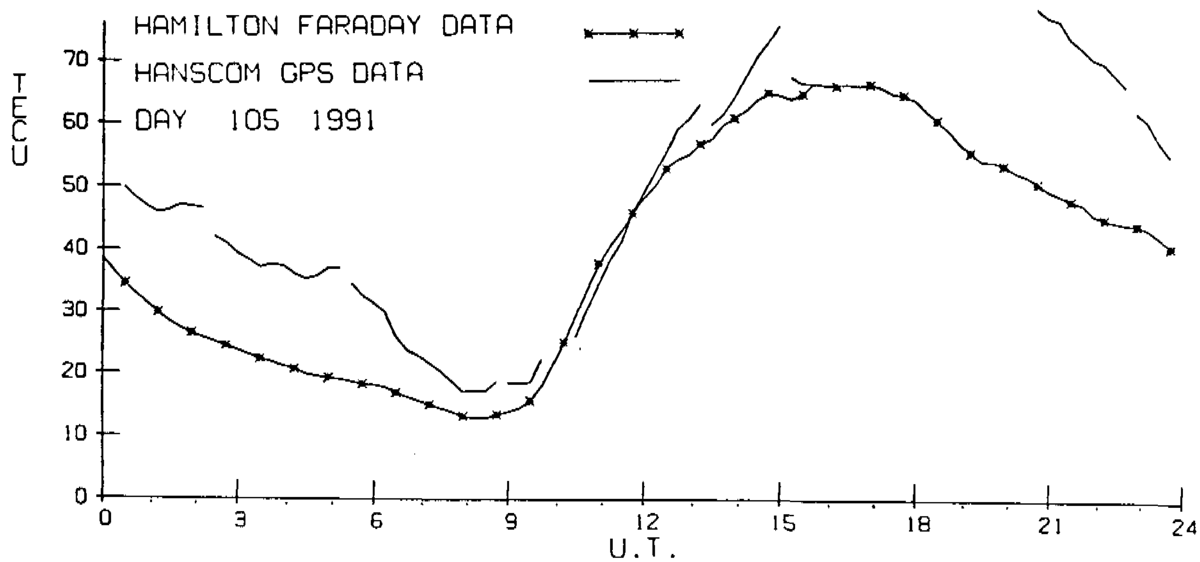

Figure 5. One day of ionospheric time delay received from a code-free GPS receiving system at Hanscom AFB, MA.

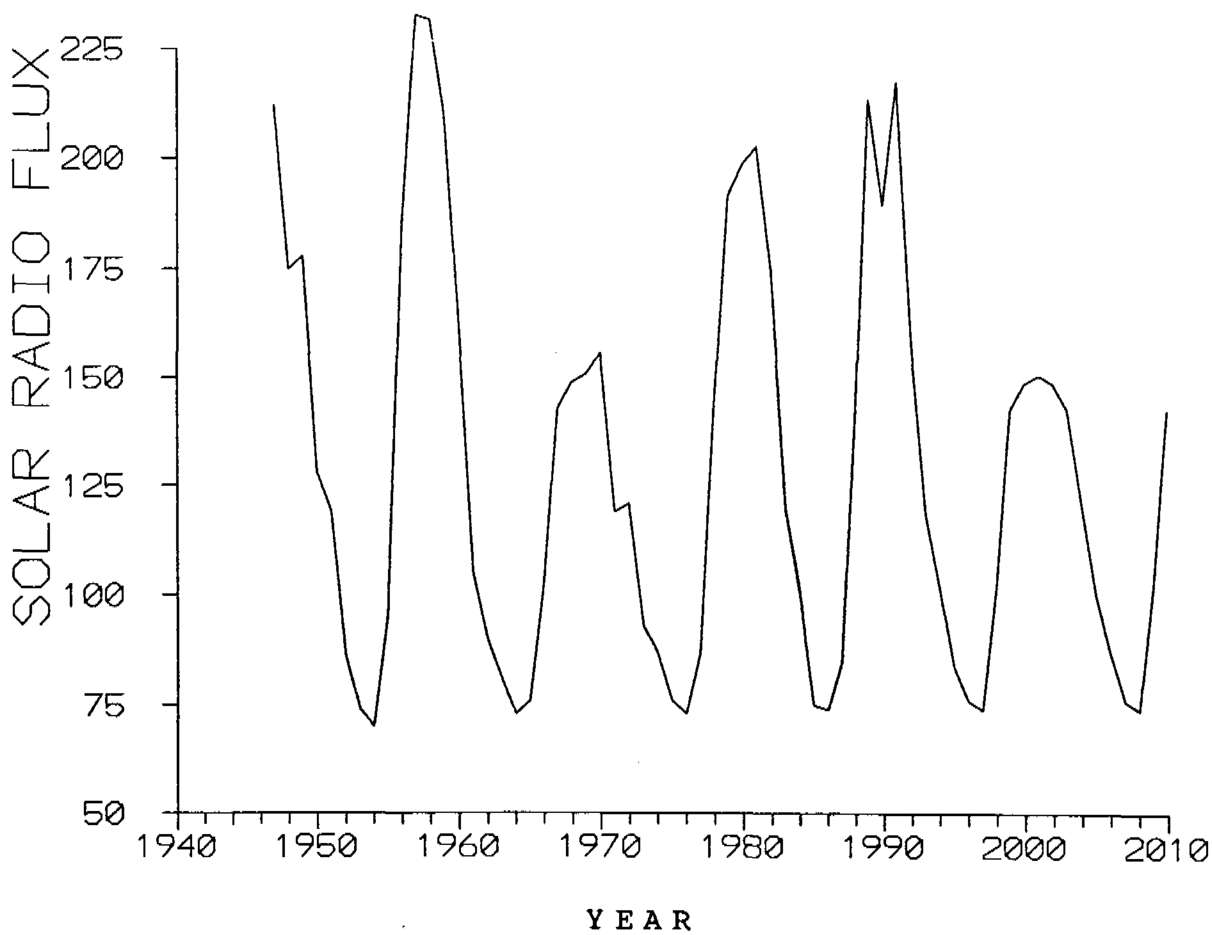

Figure 7. Mean yearly solar activity for the last four solar cycles and projections for the next cycle.

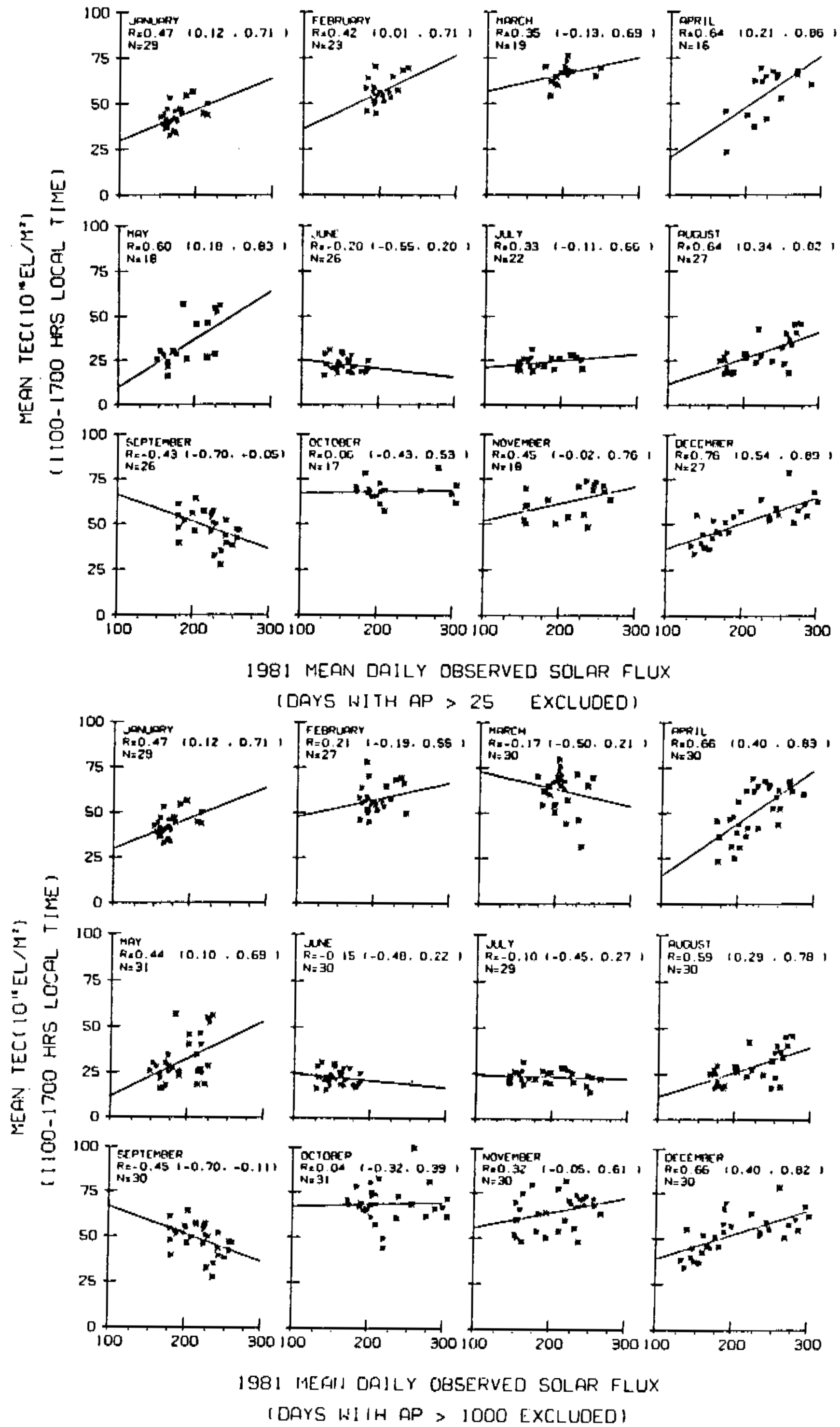

Figure 6. Correlation of mean daytime TEC from Hamilton, MA against $F_{10.7}$ for the twelve months of 1981 for magnetically quiet days (6a, top portion) and with all days included (6b, bottom portion).

QUESTIONS AND ANSWERS

Dr. William Klepczynski, USNO: A comment along the lines of "the ghost of Christmas present". At the ION meeting in September we gave a paper where the problem is even compounded more by the transmitted model by GPS. There is a maximum number for the solar flux unit that can be transmitted. The current values of solar flux exceed that value. There is a truncation problem that makes the transmitted model incomplete when the sun really acts up.

Mr. Klobuchar: Yes, it was very bad during January and February. I don't know what to do about that. If JPO would give a little money to think about it, we could try to update the model. There is a later set of data now that we could use to improve that algorithm, but I don't think that there is much interest at JPO.

Dr. Henry Fliegel, Aerospace: It is not known as well as it should be, perhaps, that JPO no longer directs the day to day operations of GPS. That is really in the hands of Space Command. The one thing that JPO can do, of course, is to revise the software to take care of this truncation problem that Bill and you have just been discussing. I guess that we should work on that so that we will be ready for the next solar maximum. The other comment that I have is that, although frankly the relations between JPO and Space Command have been very, very poor over the last few years, I think that under the new joint command for GPS, the Air Force will be more responsive to things like this.

Mr. Klobuchar: Without getting into the politics of the situation, it is not just a truncation problem. It is because the algorithm coefficients themselves were designed only up to an average solar cycle maximum. We didn't accurate time delay information that incorporated even the 1981 cycle, let alone the present cycle. However, now that is available. It would require a lot of looking at the data and new coefficients and a new model. I think that it is not a problem for the operational side, but for the Space Systems Division side.

Samuel Ward, JPL In looking at the data there, and being aware that the ionization of the atmosphere by the solar flux is a function of the angle that the flux strikes the atmosphere. That angle is a function of the tidal bulge caused by solar, earth, lunar rhythms. Could this cause some of the problems that you see?

Mr. Klobuchar: What causes the long term solar behavior is not something that I don't really want to comment on. Some people have said that most of the angular momentum of the solar system is due to the planet Jupiter, since it is the heaviest planet. So somehow Jupiter "sucks out" the sunspots from the sun. The period of Jupiter is about 11 years. Having said all of that, I shouldn't have because that smacks to me of astrology. The people who are the real solar experts don't have a good handle on what causes the cycles. They are starting to understand the shorter term stuff a little, but not the long term. They know less about forecasting solar cycles than we do about the weather. JPL is starting to give some excellent data on the ionospheric measurements around the world because they are scattering the ROGUE receivers around and are getting a lot of data. With that data, it may be possible to make a world wide model of planetary time delay, directly, within the next five years or so.

Dr. Claudine Thomas, BIPM: You forgot to mention that there is another form of codeless receiver that was developed at BIPM and reported At the PTTI in Redondo Beach. It is now available in commercial form, coupled with a GPS receiver. That receiver is used at BIPM.

Mr. Klobuchar: Yes, I didn't mean to go into the commercial units, but there are several out there. You should realize that the rights to commercial use of them belongs to Pete McDoran, who did the work when he was at JPL. The sequence is probably JPL, NIST with the French group, and the Japanese.